Electrostatic tuning of optomechanical cavities to semiconductor quantum dots

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Abstract: The integration of optomechanically coupled photonic crystal cavities to indium arsenide quantum dots is studied experimentally and theoretically. Electrostatic tuning results for one- and two-dimensional photonic crystals are presented.

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A significant challenge in the development of coherent device physics using self-assembled semiconductor quantum dots (QDs) is the wide distribution of transition energies from dot-to-dot on a given sample. This inhomogeneity stems from random nucleation during the island formation stage of growth [1]. Thus, a tunable architecture is necessary when resonantly addressing single QDs with a photonic device. Techniques such as temperature [2, 3], digital etch [4], stark shift [5], and thin-film vapor condensation [6, 7] tuning have been successfully utilized to scan the detuning of nanocavities to single QDs in cavity quantum electrodynamics (QED) experiments, but have the drawbacks of being slow and limited in tuning range, and can contribute to deterioration of the QD and cavity. Recent progress in optomechanical systems suggests exceptional methods of accessing the strongly-coupled exciton-photon regime. In particular, the extremely large optomechanical couplings (g) and optical quality factors (Q) observed in one-dimensional "zipper" [8, 9] and two-dimensional slotted [10] photonic crystals, when integrated with microelectromechanical systems (MEMS), can provide fast, wide-range, in-situ, continuous wavelength tuning to QD emission lines.

A scanning electron microscope (SEM) micrograph of an InP-quantum-well-based tunable zipper cavity is shown in Fig. 1(a). The device is comprised of a pair of doubly-clamped photonic crystal nanobeams, with a lattice variation in the center of the beams to confine the optical modes [8] . These localized resonances are coupled to the inter-beam gap x_g through the optomechanical coupling $g = d\omega/dx$, where ω is the frequency of the cavity mode and x is the relative displacement of the beams from the original gap x_g. Metal electrodes are deposited on the ends of the beams, enabling tuning of x_g, and therefore the resonant optical wavelength [9]. As seen in the micro-photoluminescence (PL) spectra in Fig. 1(c) of a device having $g/2\pi = -40$ GHz/nm, continuous wavelength tuning of a fundamental optical mode over a range greater than 20 nm is achieved for an applied voltage amplitude sweep of 9 V.

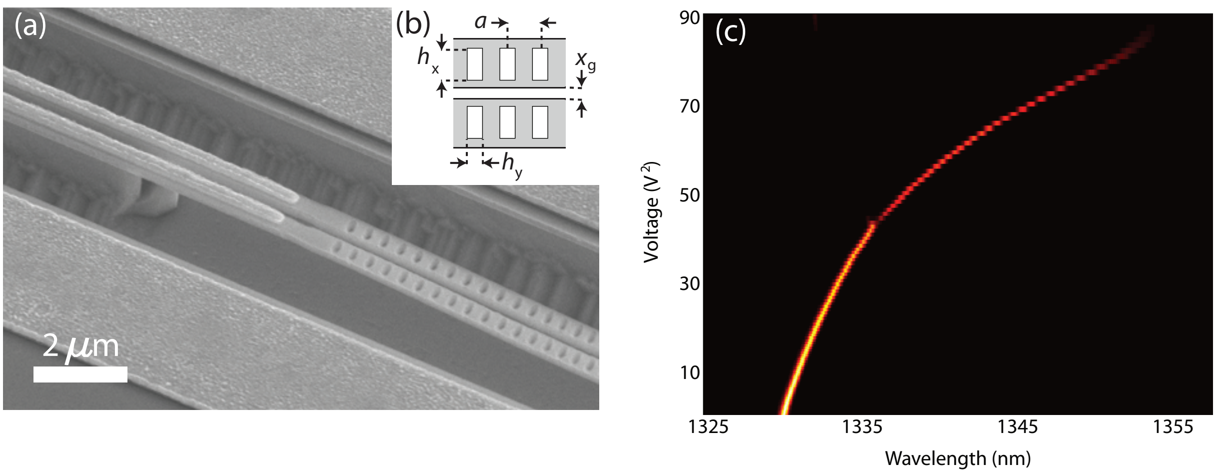

Fig. 1. (a) SEM micrograph of a zipper cavity device. (b) Schematic of the zipper cavity, the reported device features inter-beam gap $x_g = 160$ nm, lattice constant $a = 383$ nm, hole height $h_y = 240$ nm, and hole width $h_x = 120$ nm. (c) Micro-PL spectra of a fundamental optical mode versus applied voltage amplitude.

While the zipper cavity device demonstrates that electrostatic actuation is an excellent method for tuning the resonant wavelength, a number of additional benefits can be gained by using a two-dimensional slotted-cavity design. This structure has attained optical Q of greater than 10^6 and $g/2\pi = 140$ GHz/nm with extremely small optical mode volumes in Si-based devices [10]. Also, appreciable optical fields extend into the structure from the slot to the nearest hole, as illustrated by three dimensional finite-element-method (FEM) simulation for a GaAs-based device in Fig. 2(a). This feature is promising since the QD can still couple to the optical field with a rate of 9.5 GHz (39 μeV) while being positioned further than ~ 60 nm from an air surface, avoiding surface-proximity degradation of optical properties [11]. While the coupling rate is smaller than reported couplings of QDs positioned at field maxima [6], the high Q observed in slotted cavities indicates that strong-coupling is feasible in this structure. Capacitive actuation of the in-plane mode shown in Fig. 2(b) will be used to electrostatically tune the slot width.

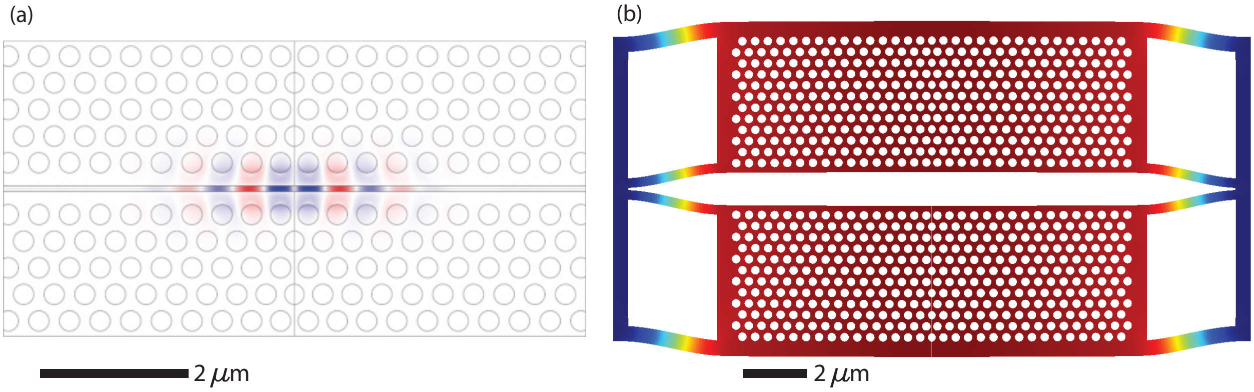

Fig. 2. FEM simulations of the fundamental (a) optical and (b) in-plane mechanical (exaggerated for display purposes) modes of the slotted cavity optimized for GaAs, with lattice constant $a = 420$ nm and hole radius $r = 140$ nm.

The structure shown in Fig. 2 is optimized for operation in GaAs with resonant optical wavelengths coinciding with QD emission lines in the 1.3 μm band. Ongoing work focuses on fabrication of an in-situ tunable slotted cavity in QD material. Up to date experimental progress will be presented.

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